

ENGINEERING STEELS

ACCIAI LEGATI DA COSTRUZIONE

Acciai **trattati termicamente** per ottenere resistenze maggiori di 750 MPa; in questa classe vengono considerati anche gli acciai MarAging – PH precipitation hardened capaci di sviluppare $\sigma_t > 2000 \text{ MPa}$ ($\sigma_y/\sigma_t > 0,9$)

Per ottenere queste resistenze si deve introdurre il concetto di “**temprabilità**” che riguarda più la possibilità di ottenere una certa durezza ad una certa profondità del pezzo piuttosto che il valore massimo di durezza e/o resistenza.

Fondamentalmente le nozioni principali furono sviluppate negli USA negli anni '30 da persone quali Grossman, Bain, Grange, Jominy, Lamont...; questo periodo coincide anche con l'introduzione dei diagrammi TTT – CCT.

Questi acciai devono contenere un tenore di carbonio sufficientemente elevato affinché l'acciaio sia suscettibile di indurire con il trattamento di tempra ($0.15 < C < 0.65$).

Fino alla fine degli anni '40 questi acciai contenevano quantitativi anche elevati di Ni e Mo; si pensava infatti che questi due elementi fossero indispensabili per conferire agli acciai sufficiente resistenza e tenacità.

La seconda guerra mondiale costrinse gli studiosi a capire meglio l'influenza degli elementi di lega e quindi si poterono sostituire questi due elementi con altri, meno costosi, quali Mn, Cr e B.

L'idea della riduzione dei costi venne poi prepotentemente riproposta negli anni '70 e '80 con la scoperta e l'introduzione sul mercato degli acciai microlegati (che non costano di meno solo per gli elementi di lega risparmiati ma anche per l'assenza del trattamento termico di tempra).

Il controllo delle inclusioni si è rivelato anche fondamentale per aumentare certe caratteristiche (ad esempio fatica) → negli anni '50 si è iniziato a fare il "degassing"; nel 1960 si è iniziato con il gorgogliamento dell'Argon; negli anni '70 è stato introdotto l'affinamento e la colata sotto vuoto.

Per quanto riguarda i trattamenti termici sempre di più si fa affidamento ai "MARTEMPERING" e "AUSTEMPERING"

AUSTEMPERING

Austempering is an isothermal heat treatment that produces a structure that is stronger and *tougher* than comparable structures produced with conventional heat treatments.

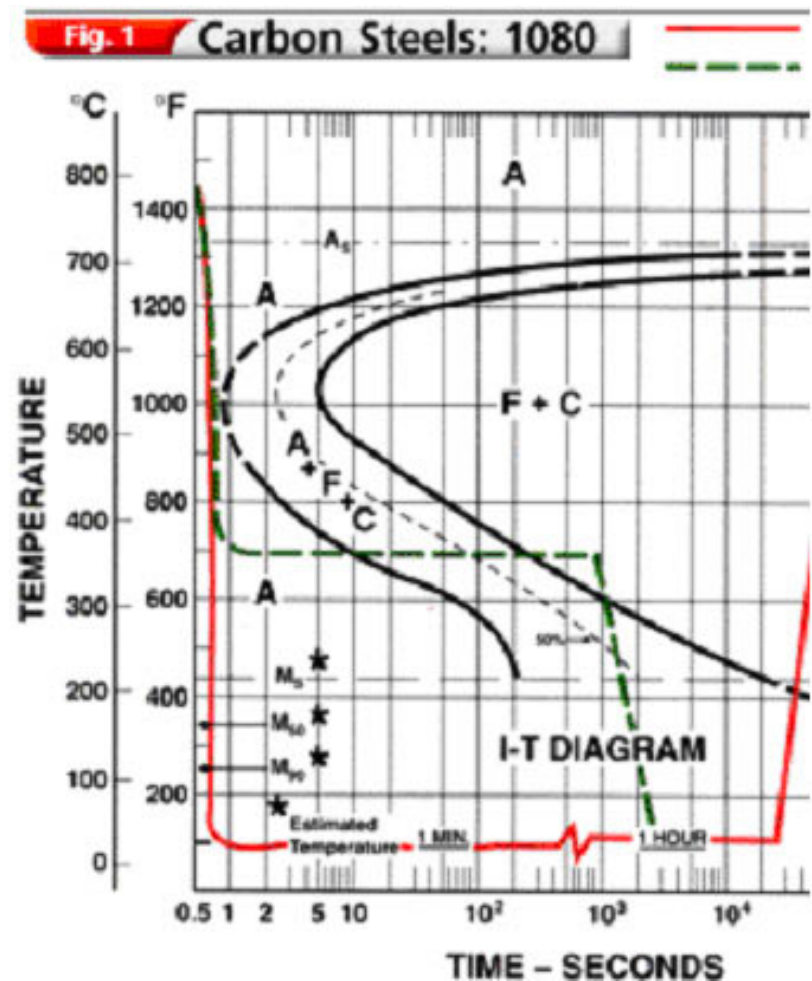
Conventional heat treaters heat the parts to "red heat" in a controlled atmosphere and then quench them in a bath of oil or water that is near room temperature. This produces a crystalline structure known as Martensite, a hard, brittle phase. The parts are then tempered in another furnace at 177 C to 593 C to decrease the "brittleness."

Austempering starts the same way. The parts are heated to red heat in a controlled atmosphere (so they don't scale) **but then are quenched in a bath of molten salt at 232 C to 399 C.** The quench temperature is above the Martensite starting temperature. Therefore, a different structure (not Martensite) results: **Bainite.**

Austempering Means Uniform Structure

During the process of quenching to Martensite, the Martensite reaction begins immediately. The result is that the outside of the part may already be transformed while the inside is still red hot. It is this "non-uniform phase transformation" that results in distortion and tiny micro cracks that lower the strength of the part.

By contrast, the Austempering reaction that produces Bainite takes place over many minutes or hours. This results in uniform growth and a stronger (less disturbed) microstructure.



Advantages of Austempering:

- Less Distortion
- Greater Ductility
- Parts are plater friendly due to the clean surface from the salt quench
- Uniform and consistent Hardness
- Tougher and More Wear Resistant
- Higher Impact and Fatigue Strengths
- Resistance to Hydrogen Embrittlement

You should use the Austempering process if:

Material used: SAE 1050 to 1095, 4130, 4140

Material thickness between 0.008 and 0.150 inches.

Hardness requirements needed in between HRC 38-52

Limitations of Austempering:

Austempering can be applied to parts where the transformation to pearlite can be avoided. This means that the section must be cooled fast enough to avoid the formation of pearlite. Thin sections can be cooled faster than the bulky sections. *Most industrial applications of austempering have been limited to sections less than 1/2 in. thick.*

MARTEMPERING

Hardening in oil is not the safest way to quench steel, in view of the risks of distortion and hardening cracks.

These risks can be reduced by means of **martempering**.

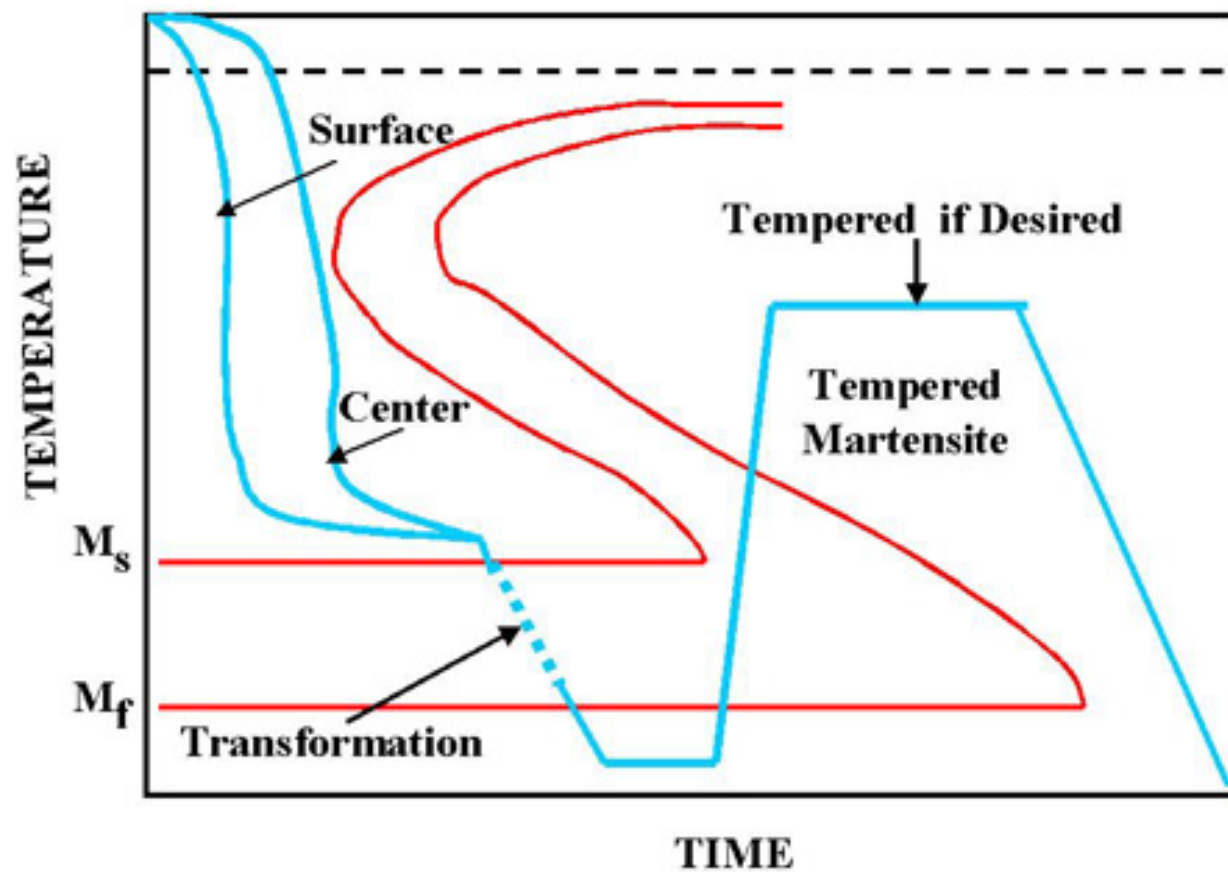
In this process, the material is quenched in two steps.

First it is cooled from hardening temperature in a salt bath whose temperature is just above the M_s temperature. It is kept there until the temperature has equalized between the surface and the core, after which the tool can be allowed to cool freely in air down through the martensite transformation range.

When martempering oil-hardening steels, it should also be kept in mind that the material transforms relatively rapid and should not be kept too long at the martempering bath temperature. This can lead to excessive bainite transformation and the risk of low hardness.

Martempering in salt bath produces a good finish, high hardness and less risk of excessive distortion or cracking.

MARTEMPERING



HARDENABILITY

Hardenability is the ability of a steel to partially or completely transform from austenite to some fraction of martensite at a given depth below the surface, when cooled under a given condition.

For example, a steel of a high hardenability can transform to a high fraction of martensite to depths of several millimetres under relatively slow cooling, such as an oil quench, whereas a steel of low hardenability may only form a high fraction of martensite to a depth of less than a millimetre, even under rapid cooling such as a water quench.

Hardenability therefore describes the capacity of the steel to harden *in depth* under a given set of conditions.

Steels with high hardenability are needed for large high strength components, such as large extruder screws for injection moulding of polymers, pistons for rock breakers, mine shaft supports, aircraft undercarriages, and also for small high precision components such as die-casting moulds, drills and presses for stamping coins.

High hardenability allows slower quenches to be used (e.g. oil quench), which reduces the distortion and residual stress from thermal gradients.

Steels with low hardenability may be used for smaller components, such as chisels and shears, or for surface hardened components such as gears.

Hardenability can be measured using the Jominy end quench test.

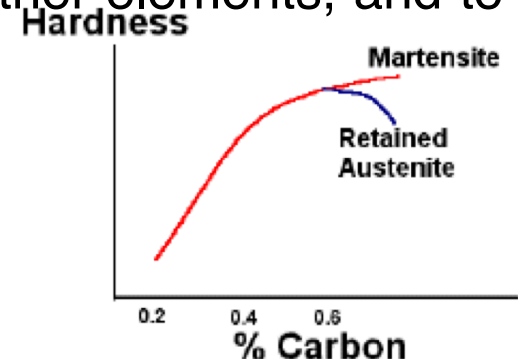
Alloying elements

The main alloying elements which affect hardenability are C, B and a group of elements including Cr, Mn, Mo, Si and Ni.

Carbon

Carbon controls the hardness of the martensite. Increasing the carbon content increases the hardness of steels up to about 0.6wt%. At higher carbon levels, the formation of martensite is depressed to lower temperatures and the transformation from austenite to martensite may be incomplete, leading to retained austenite. This composite microstructure of martensite and austenite gives a lower hardness to the steel, although the microhardness of the martensite phase itself is still high.

It is more common to control hardenability with other elements, and to use carbon levels of less than 0.4wt%.



Boron

Boron is a very potent alloying element, typically requiring 0.002 to 0.003wt% to have an equivalent effect as 0.5wt% Mo.

The effect of B is also independent of the amount of B, provided sufficient is added, and the effect of B is greatest at lower carbon contents.

It is typically used with lower C steels. B has a very strong affinity for oxygen and nitrogen, with which it forms compounds.

Boron can therefore only affect the hardenability of steels if it is in solution. This requires the addition of "gettering" elements such as aluminium and titanium to react preferentially with the oxygen and nitrogen in the steel.

Chromium, molybdenum, manganese, silicon, nickel, vanadium

The elements Cr, Mo, Mn, Si, Ni and V all retard the phase transformation from austenite to ferrite and pearlite. The most commonly used elements are Cr, Mo and Mn.

The retardation is due to the need for redistribution of the alloying elements during the diffusional phase transformation from austenite to ferrite and pearlite.

The solubility of the elements varies between the different phases, and the interface between the growing phase cannot move without diffusion of the slowly moving elements.

There are quite complex interactions between the different elements, which also affect the temperatures of the phase transformation and the resultant microstructure.

Steel compositions are sometimes described in terms of a *carbon equivalent* which describes the magnitude of the effect of all of the elements on hardenability.

Grain size

Increasing the austenite grain size increases the hardenability of steels.

The nucleation of ferrite and pearlite occurs at heterogeneous nucleation sites such as the austenite grain boundaries.

Increasing the austenite grain size therefore decreases the available nucleation sites, which retards the rate of the phase transformation.

This method of increasing the hardenability is rarely used since substantial increases in hardenability require large austenite grain size, obtained through high austenitisation temperatures. The resultant microstructure is quite coarse, with reduced toughness and ductility.

HIGH PRESSURE GAS CYLINDERS

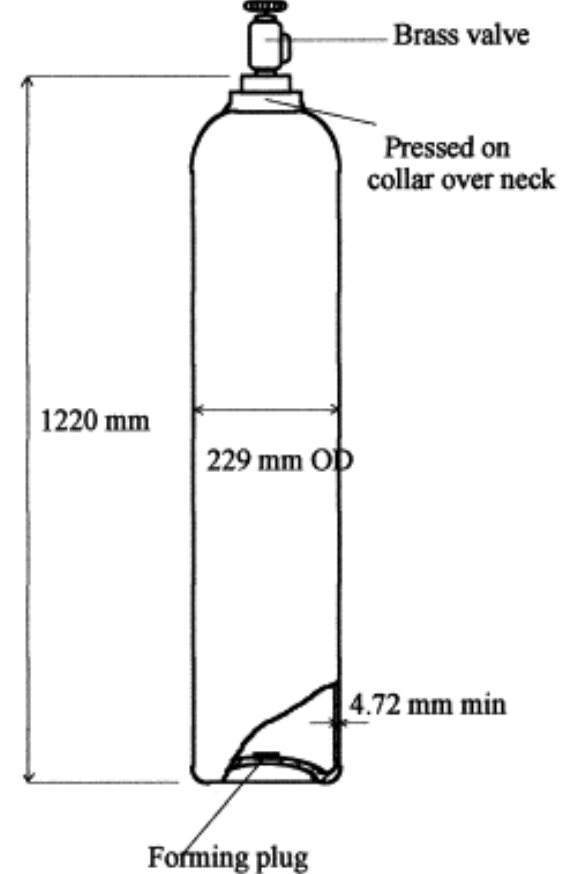
Since the first high-pressure gas cylinders were manufactured around the turn of the twentieth century (**1870**) , various types of steels have been used.

In the beginning carbon steels and low-carbon steels were the common materials.

The properties of these steels are achieved via a normalising heat treatment.

The working pressure was typically between 100 and 150 bar. Such cylinders were manufactured up to around 1960, though they are still being manufactured in other parts of the world.

The weight of such an industrial 40l. cylinder, with a nominal gas capacity of 6 m³ and a wall thickness of approx. **7.5 mm**, was more than **70 kg**.



Progress towards thinner, lighter and more efficient cylinders has been achieved mainly by the use of steels of increased yield and tensile strengths.

Yield stress is the basic value used in the design of gas cylinders and it thus indirectly determines the weight of the cylinder.

Around 1935 carbon-manganese steel was introduced but still in the normalised condition. The yield stress was slightly higher at about 400 MPa

An important technical improvement was the introduction of the quenched and tempered Cr-Mo steel which was generally accepted from 1960 onwards.

In Europe this led to an almost doubling of the yield stress from 400 MPa to between 700 to 755 MPa.

This permitted an increase of the working pressure to 200 bar along with an increase in the gas capacity at an even lower cylinder weight than before.

Since then 200 bar has been the standard pressure in most European countries. The weight of a typical 50l. industrial gas cylinder with a nominal gas capacity of 10m³ is about 60-65 kg.

In recent years the yield stress of the original Cr-Mo steel has been further increased to 850 MPa which is a figure approved and used in many countries.

The step from 150 bar to 200 bar was relatively uncomplicated as in most cases the same gas supply equipment could be used for both pressures and thus also the same valve connection threads for both pressure stages.

Since the 1990's cylinder manufacturers have offered cylinders with a yield stress of around 1000 MPa and with an increase of gas content to weight ratio.

These steels are used to develop yet another significant step in the cylinder development chain: industrial gas cylinders with a 300 bar working pressure. The weight of a 300 bar working pressure, 50l. industrial gas cylinder is around 75 kg when designed to EEC Directive 84/525.

Further developments at CEN and ISO have reduced this weight even more.

High efficiency cylinders require stronger materials and this means increasing their yield stress. However, increased yield stress normally means that greater attention should be paid to:

- toughness
- ductility
- resistance to fatigue
- corrosion resistance

To obtain an optimum balance between these factors required refinements in material quality, production methods and quality control.

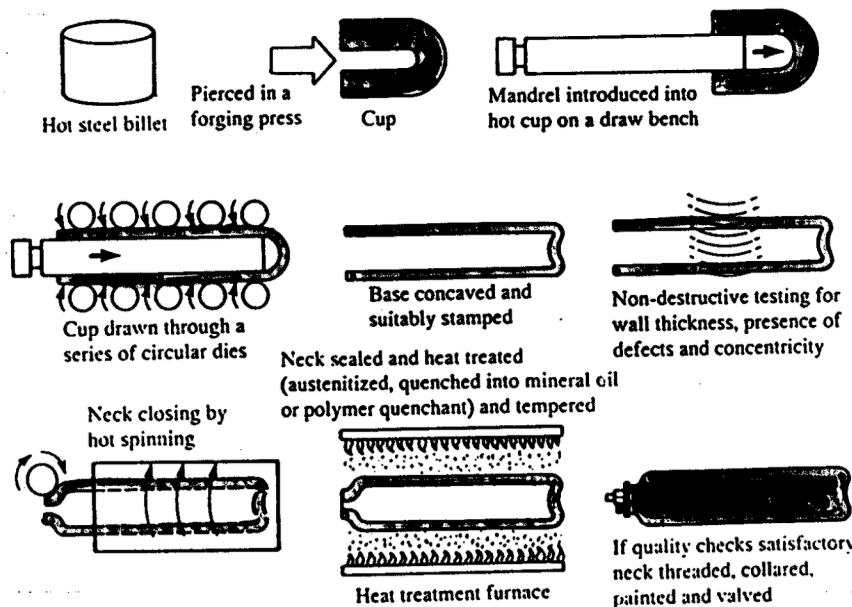
The extra requirements put on these new steels with a tensile strength above 1100 MPa have been intensively discussed within ISO TC58 and CEN TC23. An ISO standard and a European standard for the cylinder design have been issued.

Table 4.10 Seamless steel gas containers to BS 5045: Part I: 1982

Material	Code	C%	Si%	Mn%	Cr%	Mo%	Ni%	YS ^a (N/mm ²) min.	TS ^a (N/mm ²)
• Carbon steels	M	0.15–0.25	0.05–0.35	0.4–0.9	–	–	–	250	430–510
	C	0.35–0.45	0.05–0.35	0.6–1	–	–	–	310	570–680
➔ • C–Mn steels	Mn	0.4 max.	0.1–0.35	1.3–1.7	–	–	–	445	650–760
	Mn H							755	890–1030
➔ • Cr–Mo alloy steel	CM	0.37 max.	0.1–0.35	0.4–0.9	0.8–1.2	0.15–0.25	0.5 max.	755	890–1030
• Ni–Cr–Mo alloy steel	NCM	0.27–0.35	0.1–0.35	0.5–0.7	0.5–0.8	0.4–0.7	2.3–2.8	755	890–1030

^aFor containers for use in hydrogen trailer service, the minimum yield strength shall not exceed 680 N/mm² and the tensile strength shall be within the range 800–930 N/mm².

After BS 5045: Part I: 1982 Amendment No. 1, August 1986.



$$\sigma_c = p r / t$$

$$\sigma_a = p r / 2 t$$

$$\sigma_c = \text{stress circonferenziali}$$

$$\sigma_a = \text{stress assiali}$$

$$p = \text{pressione}$$

$$200 \text{ atm, } t = 5.39 \text{ mm}$$

The protection of seamless steel gas cylinders

Il Boiler & Pressure Vessel Code dell'ASME prevede, nel caso si utilizzino i comuni acciai da costruzione, che la tensione ammissibile sia **la minore** tra:

- 1/4 della tensione di rottura a trazione a T_{amb}
- 5/8 della tensione di snervamento a trazione a T_{amb}
- 1/4 della tensione di rottura a trazione alla T_{lavoro}
- 5/8 della tensione di snervamento a trazione T_{lavoro}
- la tensione che produce l'1% di creep in 100.000 ore alla T_{lavoro} ;
- l'80% della tensione che provoca rottura al termine delle 100.000 ore T_{lavoro}

BOMBOLE PER H₂

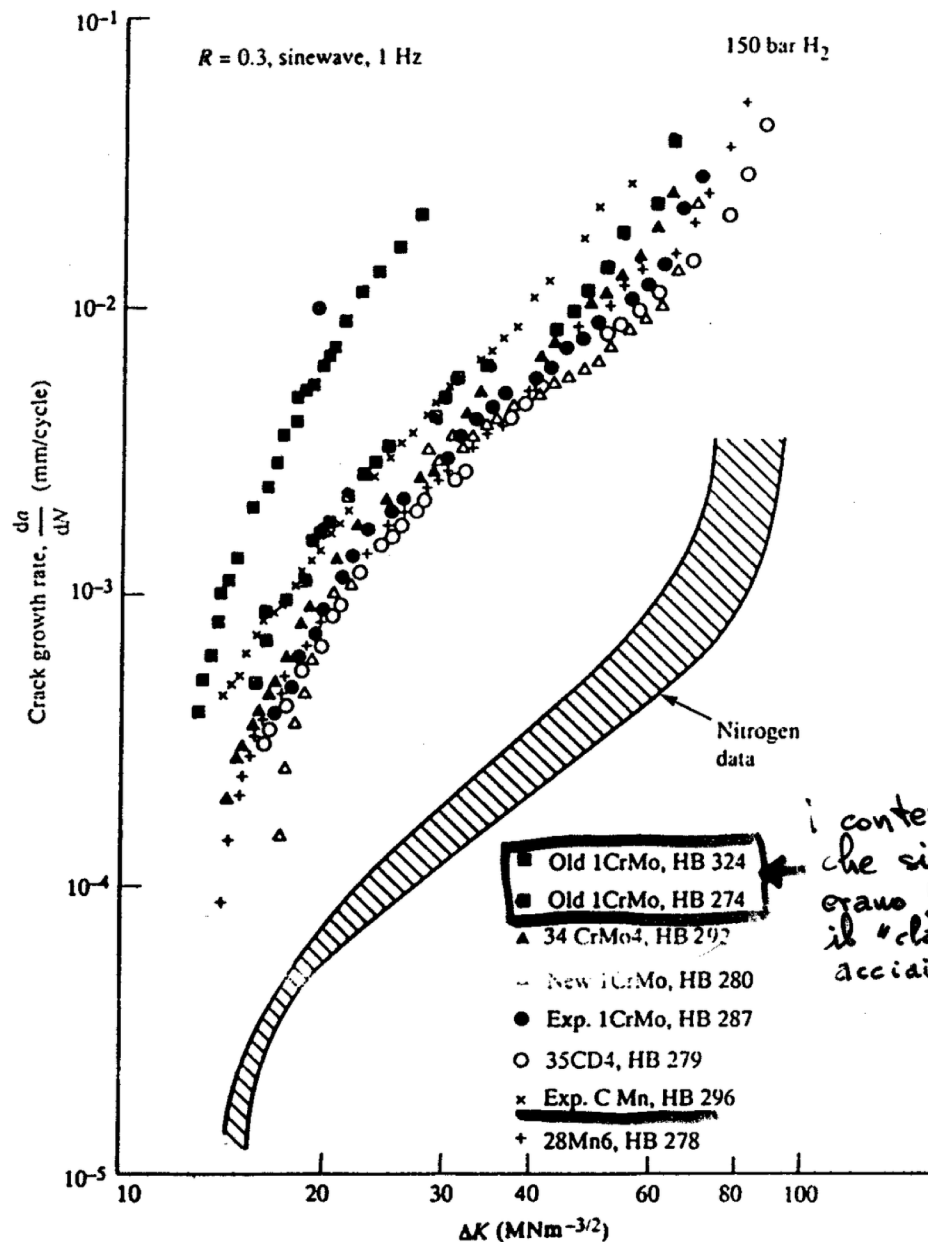
Tra il '70 e l'80 ci sono stati in Europa almeno 100 incidenti (20 in UK) di bombole contenenti H₂ scoppiate mentre venivano trasportate su camion. Le fratture erano dovute a fatica ed erano causate da piccoli difetti di fabbricazione nella superficie interna nella zona di max stress.

Le bombole erano conformi alle norme dell'epoca e non provenivano da un solo lotto.

Si scoprì che i due punti che distinguevano queste bombole dai contenitori usati per stoccare il gas erano:

- ✓ Frequenza di riempimento (anche due al giorno → stress ciclici)
(N.B. i contenitori classici ~ 12 riempimenti/anno)
- ✓ Il trasporto su camion

The risk of hydrogen embrittlement of the steel: this phenomena leads to a premature crack of the steel due to H atom dissolution and trap (stress corrosion cracking). The main risk is the burst of the tank. A lot of efforts on H₂ gas pressure embrittlement understanding and prevention rules were conducted in the 70s and 80 s after many accidents occurred with steel pressure vessels. The prevention rules based on 200 bar cylinders were then defined.



Il fattore di crescita dei cracks passa da 20 a 100 quando la durezza passa da 274 a 324HB
 È ora le norme prevedono che la durezza massima per contenitori di H_2 sia 230÷290HB e

Comunque il punto fondamentale è il controllo delle inclusioni.

i contenitori che si rompevano erano fatti con il "classico" acciaio Cr-Mo

The influence of hydrogen on the rate of fatigue crack growth in gas container steels (After Harris et al.²¹)